Saturn's upper atmospheric density profile from Doppler data during Cassini proximal orbits, with exoplanet perspective

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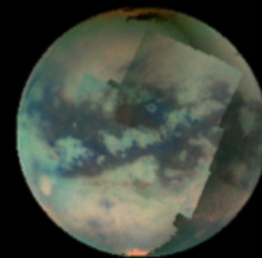
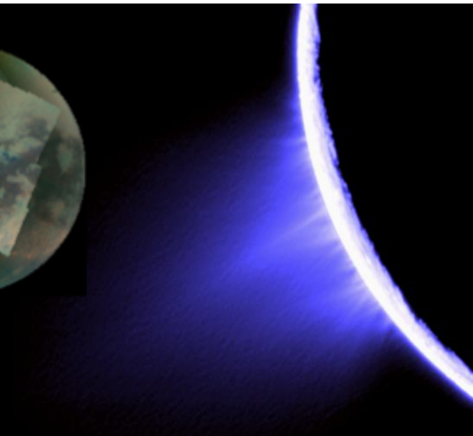
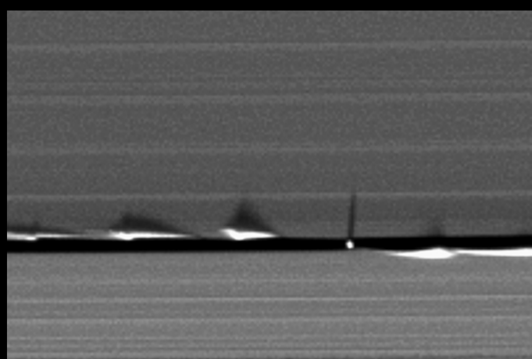
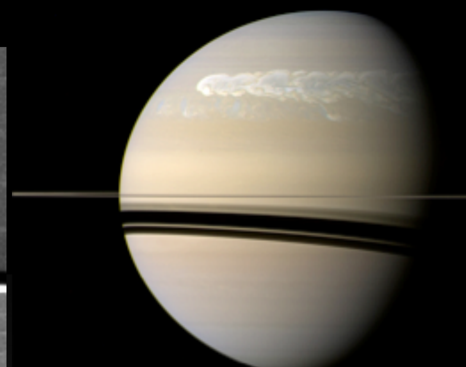
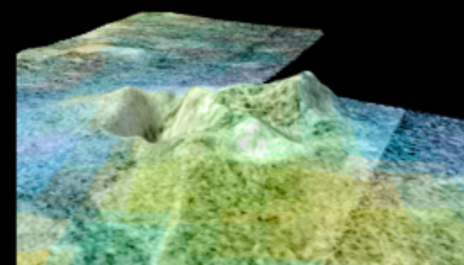
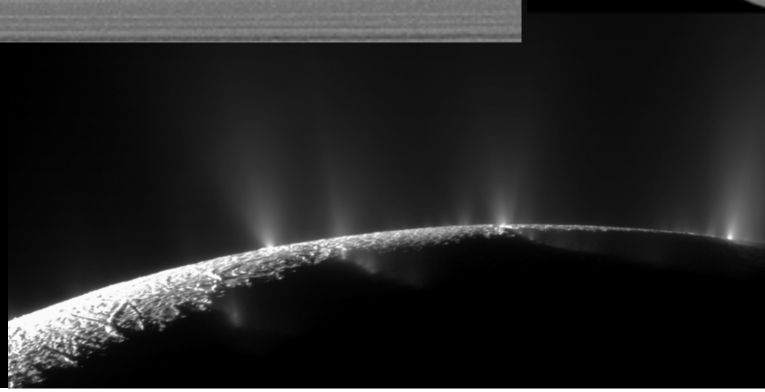
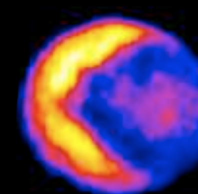
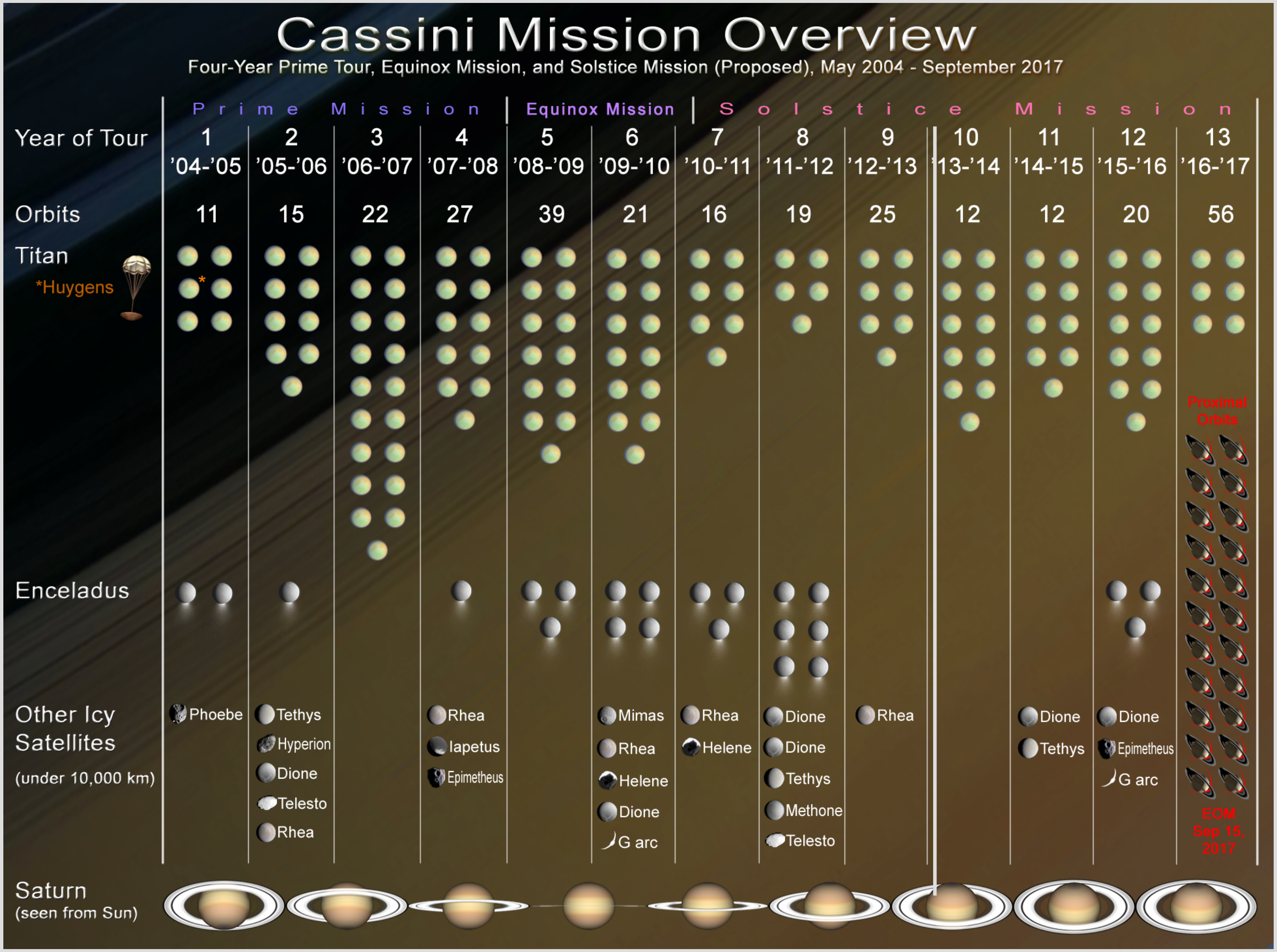
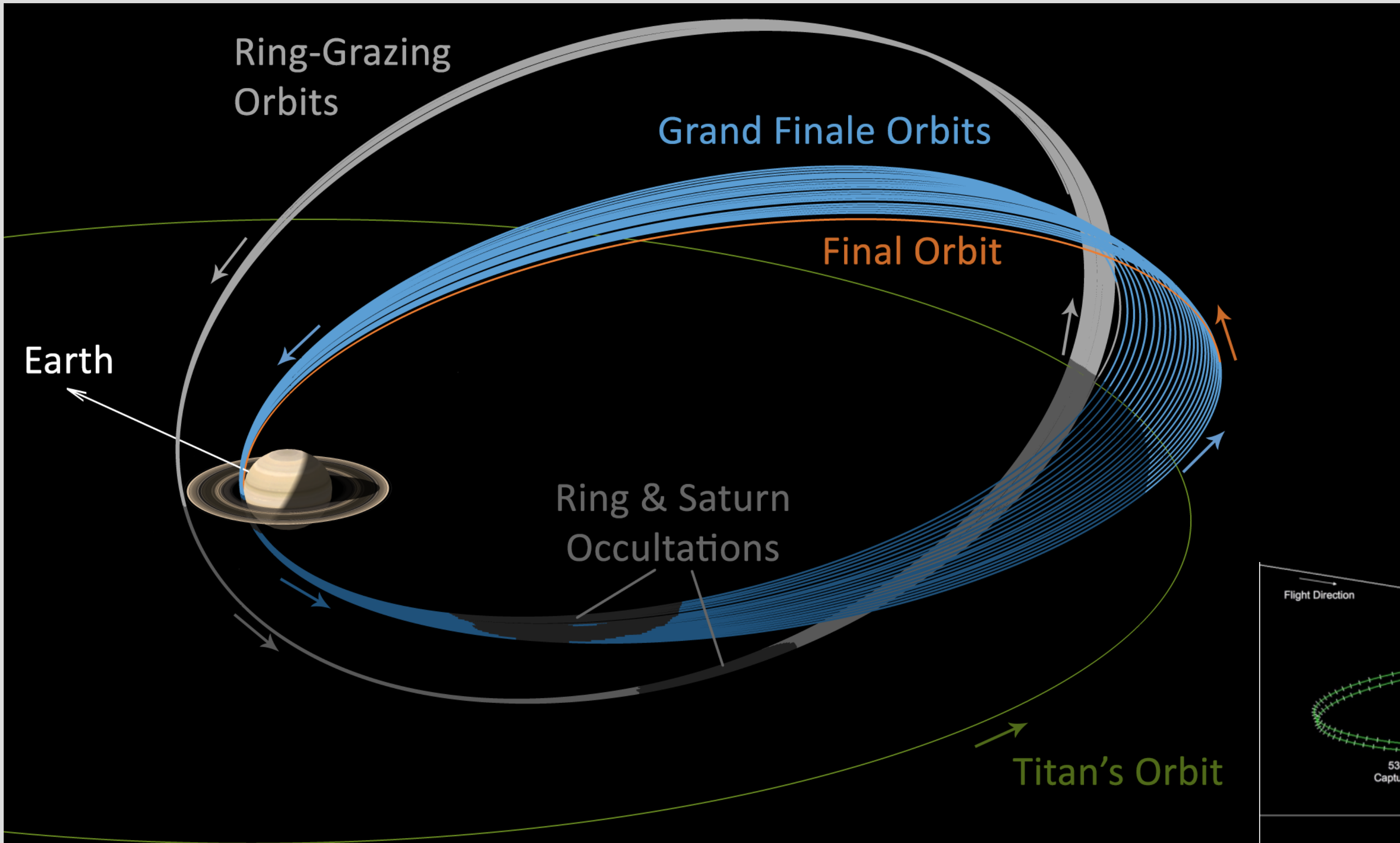
Cassini: Science Highlights

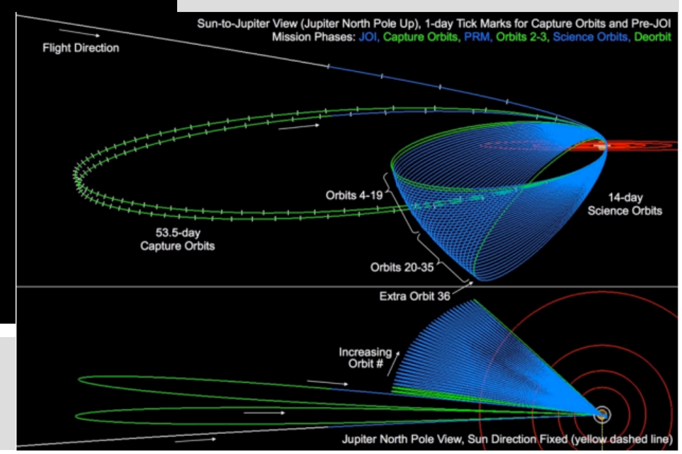









Cassini Mission Overview
Four-Year Prime Tour, Equinox Mission, and Solstice Mission (Proposed), May 2004 - September 2017
Prime Mission
Equinox Mission
Solstice Mission
Year of Tour
1 '04-'05
2 '05-'06
3 '06-'07
4 '07-'08
5 '08-'09
6 '09-'10
7 '10-'11
8 '11-'12
9 '12-'13
10 '13-'14
11 '14-'15
12 '15-'16
13 '16-'17
Orbits
11 15 22 27 39 21 16 19 25 12 12 20 56
Titan
*Huygens
Enceladus
Other Icy Satellites
(under 10,000 km)
Phoebe
Tethys
Hyperion
Dione
Telesto
Rhea
Rhea
Iapetus
Epimetheus
Mimas
Rhea
Helene
Dione
G arc
Rhea
Helene
Dione
Dione
Tethys
Methone
Telesto
Rhea
Dione
Tethys
Dione
Epimetheus
G arc
Proximal Orbits
EOM Sep 15, 2017
Saturn
(seen from Sun)

Geometry of Cassini Proximal Orbits



Juno Orbits



These orbits allow high precision measurements and/or useful constraints for:

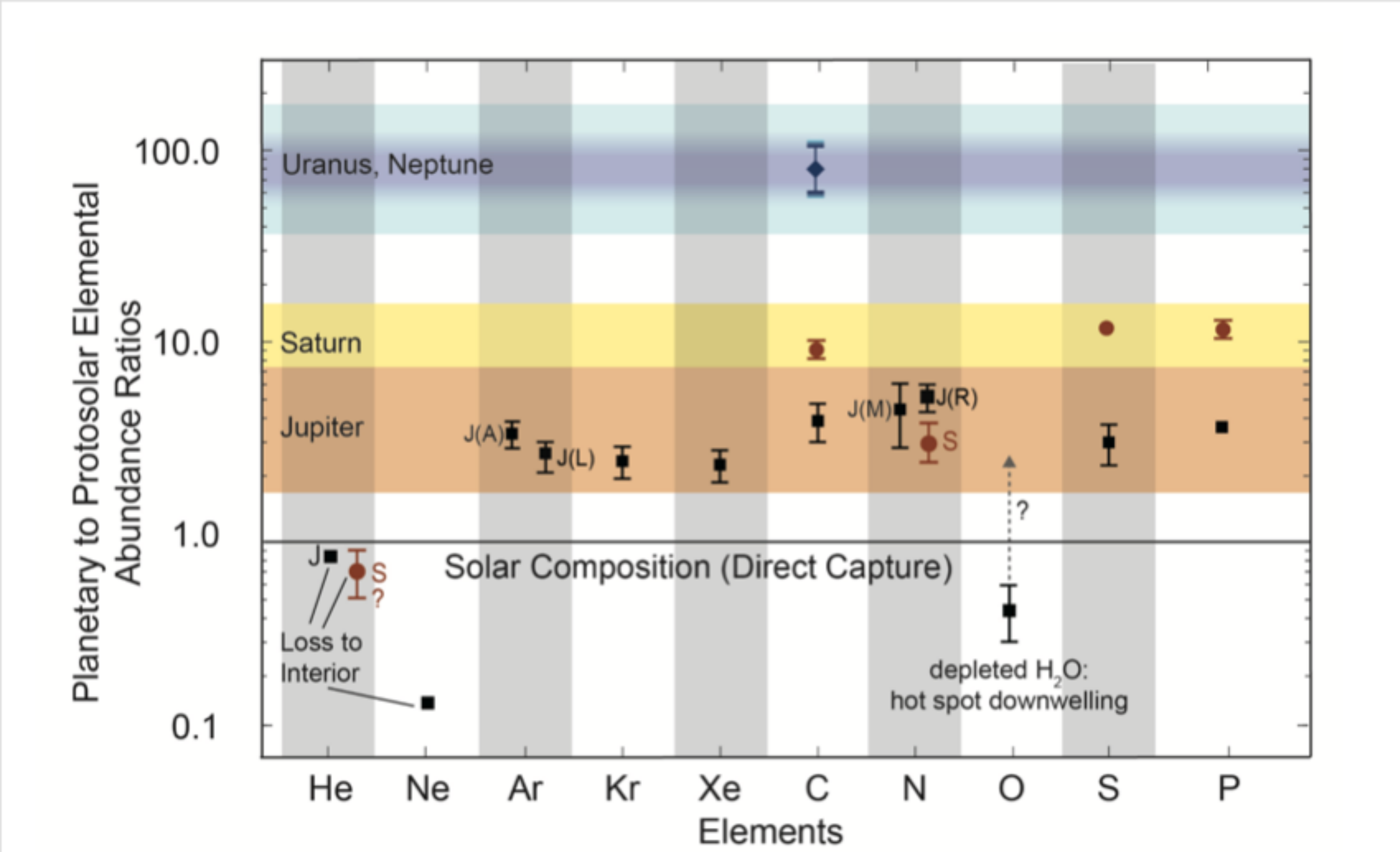
- High order moments of gravity and magnetic field
- Ring mass and particle distribution
- Internal structure
- Rotation rate
- In-situ sampling/detection of the upper atmosphere

With comparable data on Jupiter and Saturn:

-> intrinsic differences between two giant planets

-> a sense of what can be expected of extrasolar giant planets within the same stellar system
(the reverse is also true: advance in exoplanet observations can lead to deeper understanding of the Jovian planets)

Relative Protosolar Abundances of Outer Planets



From Atreya et al. 2016

The Abundance, Composition, and Loss Process of these gas giants can provide useful guidance for the understanding of their formation and evolution

Abundance: Using unique, independent navigation data to estimate the density of Saturn's upper atmosphere

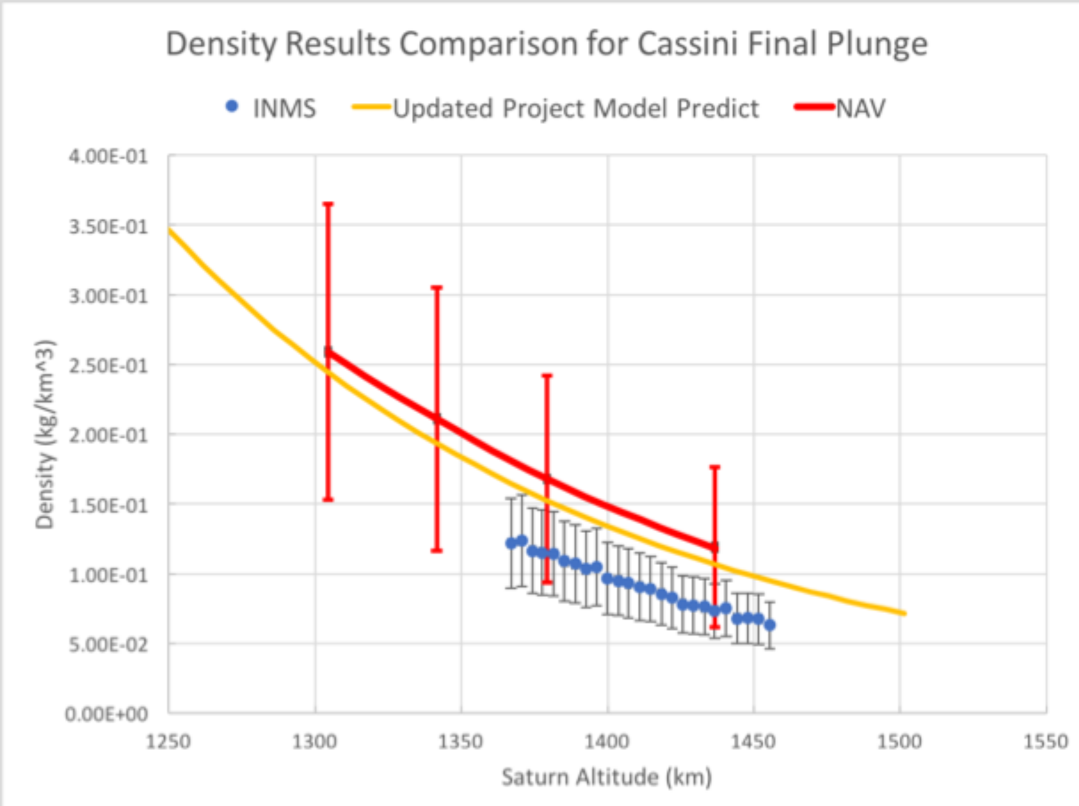
Loss Process: Atmospheric escape modeling that is applicable to exoplanetary atmospheres

Cassini's Final Plunge:

- Ballistic trajectory, final five Saturn periapses flying between rings and atmosphere
- Final untargeted, distant flyby of Titan places spacecraft on impacting trajectory
- Plunge into atmosphere with High-Gain Antenna on Earth-point
- Collect Doppler data until drag torques antenna off Earth
- Line of sight velocity change information used to fit correction to Saturn atmospheric density profile
- Only chance for navigation team to directly investigate Saturn atmosphere
- One of the Cassini Mission's final science investigations

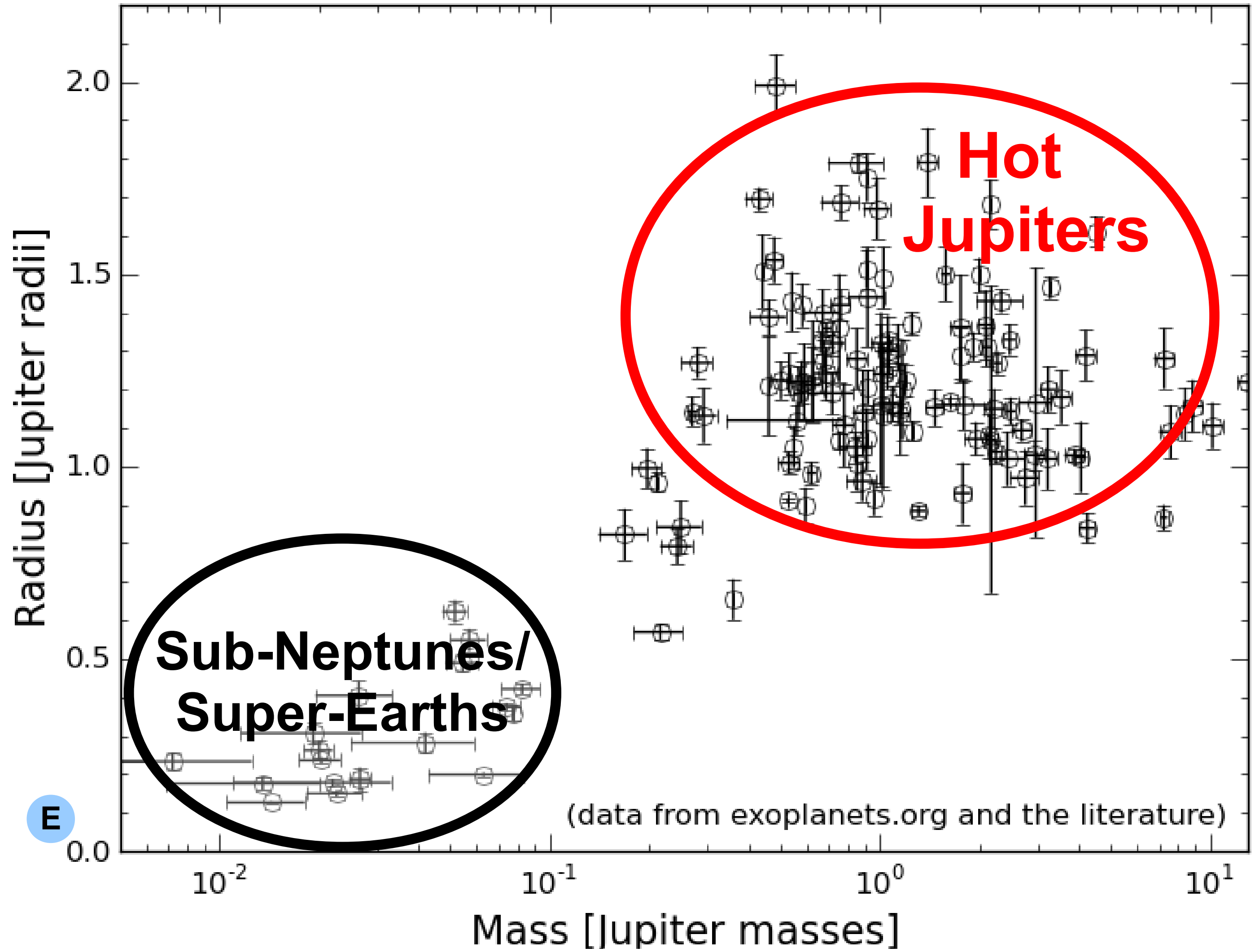
Comparison to results from other sources

- Error bars plotted as +/- 1σ
- Predicted atmosphere based on data from last five Saturn revs, scaled up from nominal project atmosphere model
- INMS counts converted to mass density assuming H2 atmosphere



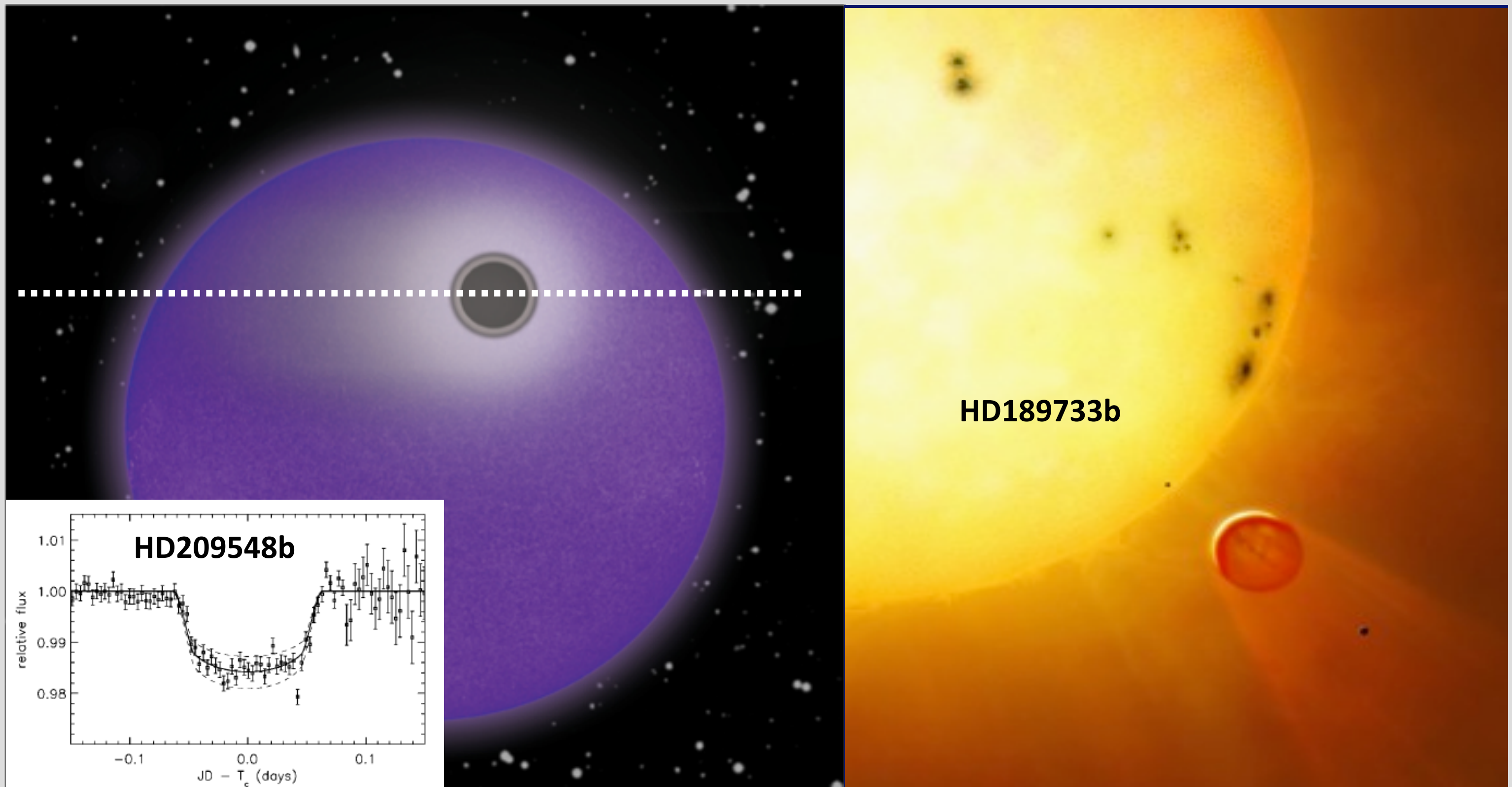
Boone et al, 2018

Transiting Planets with Measured Masses:



Escape from Transiting Exoplanets Atmospheres

Driven by *heating* of upper atmosphere by UV/EUV or X-rays



HD209548b: Lyman α drop ~ 15% but occultation is 1.5%
HD189733b: enhanced Lyman α drop after X-ray burst

Thermal and Non-thermal Escapes

- Thermal
  - Jeans escape (evaporation)
  - Hydrodynamic blow-off (bulk fluid flow)

- Non-thermal
  - Dissociative recombination: $A_2^+ + e \rightarrow A^* + A^* + \Delta E$
  - Photodissociation: $A_2 + \nu \rightarrow A^* + A^* + \Delta E$
  - Charge exchange: $A^+ + B^* \rightarrow A + B^+$
  - Atmospheric sputtering: $A^+ + B \rightarrow A^+ + B^*$

Fluid Equations & Escape

e.g., solve 1D radial equations: Jeans parameter: λ = U/ kT

$$\frac{1}{r^2}\frac{\partial}{\partial r}(r^2\rho v)=0$$

$$\frac{\partial}{\partial r}\left(\frac{1}{2}v^2\right)+\frac{1}{\rho}\frac{\partial p}{\partial r}+\frac{GM}{r^2}=0$$

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2\left\{\rho v\left(\frac{1}{2}v^2+\tilde{c}_pT+U\right)-\kappa\frac{\partial T}{\partial r}\right\}\right]=\underset{\sim}{q}$$

Given n_o , T_o at lower boundary r_o & q (*heating + radiative cooling*)

still need upper boundary conditions

collisional → collisionless

Typically Assume

a sonic point (blow-off): **$2\ m\ c_s^2 \cong U(r_s)$**

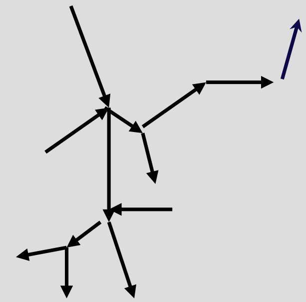
If conduction is inefficient

Integrated energy eq. → $\varphi_{es} \sim\ Q_{net}\ /\ U(r_{UV})$

or

Jeans escape (modified Jeans)

Test Hydrodynamic Models of Escape



Molecular Kinetic Simulations

Direct Simulation Monte Carlo (DSMC)
(e.g. Bird 1994)

Equivalent to solving Boltzmann equation for a gas

- **Simulate atmosphere using representive molecules with weights**
- **Track molecules in gravity field subject to collisions & heating**
- **MC choice of collision outcomes: cross sections**
- **Gas properties constructed from density & speed distributions**

Kn = Mean free path for collision/ length scale

Kn < ~ 0.1 Fluid equations

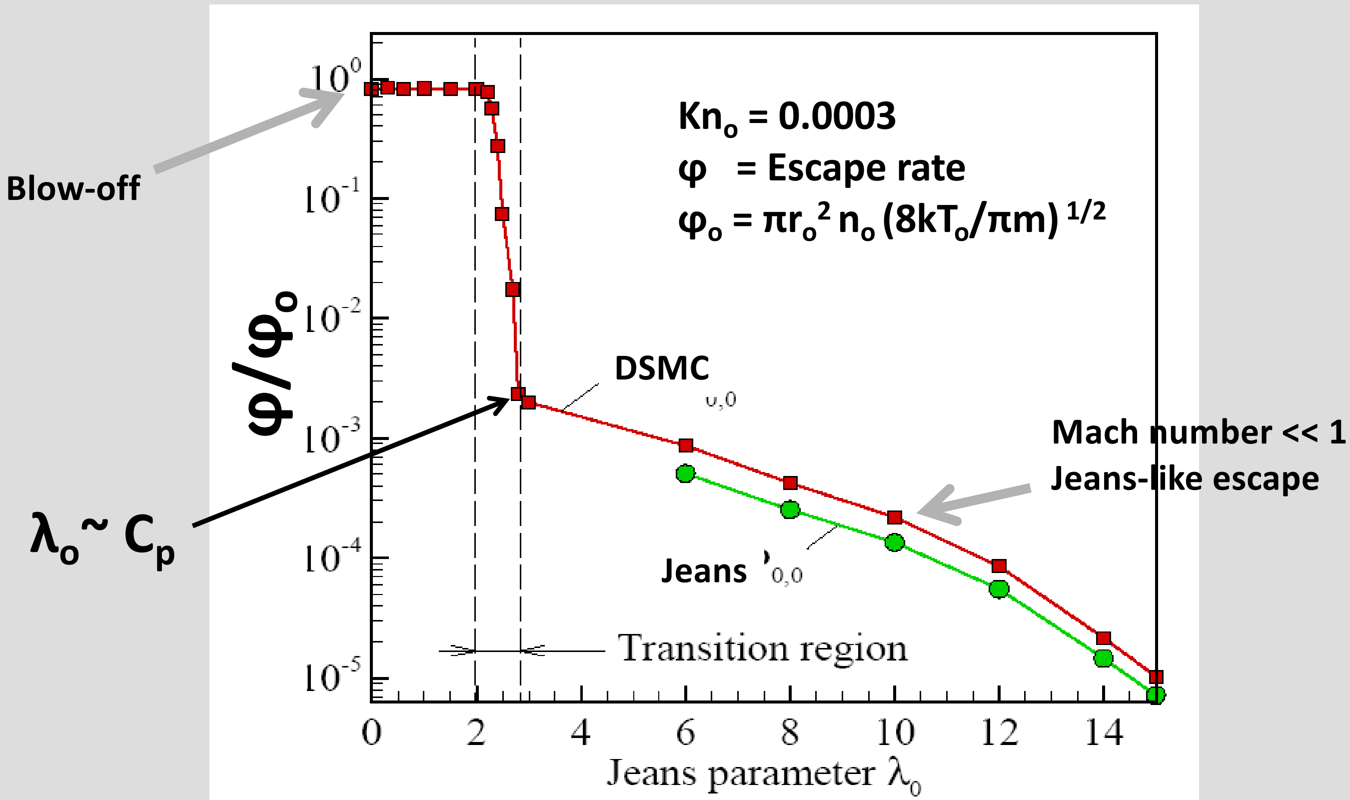
Exobase: Kn ~ 1 → high prob. of molecular escape

Use Molecular Kinetic Model to:

Check the energy limited escape rate
Check validity of using Jeans bc
Find a criterion for when the atmosphere goes sonic
Test the sonic solutions

Scaled Escape Rate: $Q = 0$ for $r > r_o$

Volkov et al. 2011; Gruzinov 2011



Hydrodynamic → Jeans Escape occurs over *narrow* range of λ

Energy limited escape is reasonable

(with a major caveat: heating efficiency)

But flow *not* necessarily transonic

Blow-off (Transonic)
Hydrodynamic escape

↓

T & n decrease rapidly
Concentrations ~ const.

Evaporative (Subsonic)
Jeans-like escape

↓

T & n decrease more slowly
Diffusive separation

Affects: Escape of trace species
Interaction with external fields
UV/EUV absorption radius

Transonic Threshold?

$\phi \sim Q_{net} / U(r_a) \sim n_s c_s 4 \pi r_s^2$

$c_s^2 \sim U(r_s)/2m$

$Kn(r_s) < Kn_m \sim < 0.1$

$Q_{net} > 4 \pi (2U(r_s)/m)^{1/2} U(r_a) \gamma /(\sigma_c Kn_m)$

r_a is the mean absorption depth

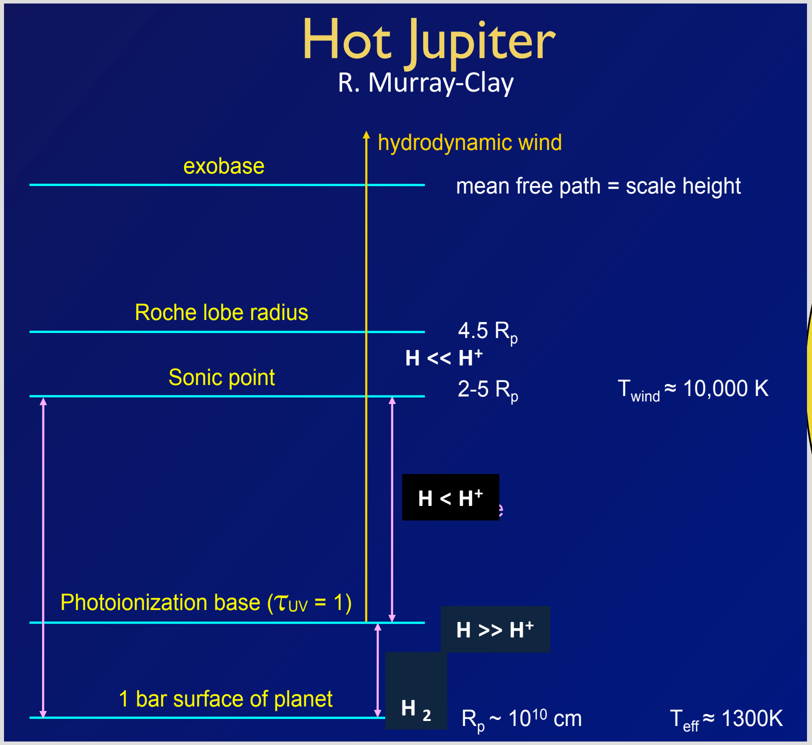
r_s is the sonic point ($> r_a$)

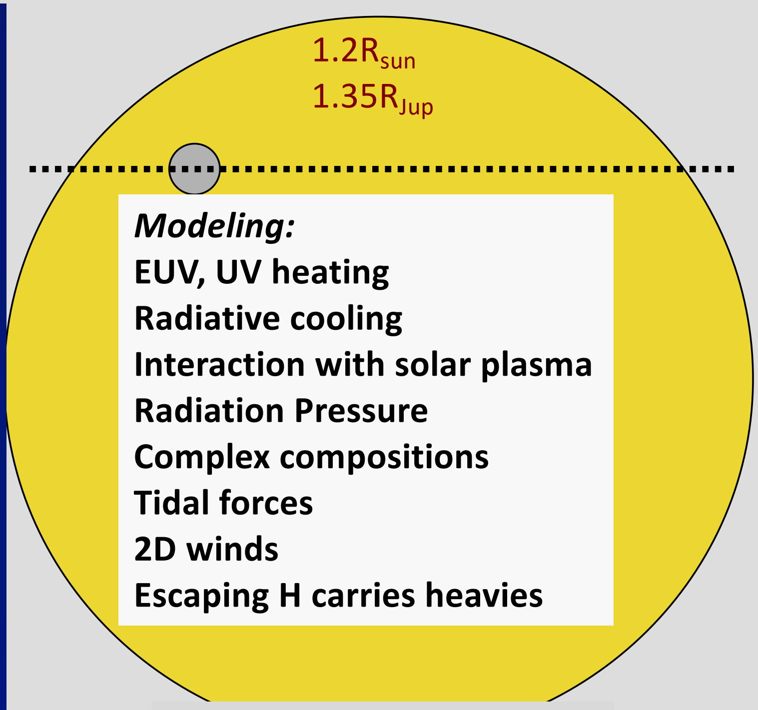
$Q_{net} = \varepsilon 4\pi r_a^2 F_{UV/EUV}$ – radiative cooling

ε = 'heating' efficiency

Modeling Exoplanet Atmospheres

HD209458b





Detected: H, Na, OI, CII, SIII

Similar loss rates with different thermal escape modeling

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